MODELING OF CLOUD SCALE TURBULENT TRANSPORT

W. Steve Lewellen
MAE Dept., PO Box 6106, West Virginia University
Morgantown, WV, 26506 6106
Phone: 304 293 3111 (x371), Fax: 304 293 6689
E-mail: slewellen@cemr.wvu.edu

David C. Lewellen
MAE Dept., PO Box 6106, West Virginia University
Morgantown, WV, 26506 6106
Phone: 304 293 3111 (x332), Fax: 304 293 6689
E-mail: lewellen@coe.wvu.edu

LONG TERM GOALS

Our long term goals are to understand the dynamics of atmospheric motions on scales of 10 kilometers and less in sufficient detail to be able to provide a consistent subgrid scale turbulent closure for models across a range of scales, and to be able to utilize simulated variances as a measure of forecast predictability.

OBJECTIVES

The objective is to develop a consistent closure model for cloud scale turbulence that would allow one to produce a simulation at any desired level of resolution, with the results of lower resolution simulations being approximately similar to results obtained by appropriate spatial filtering of the higher resolution simulation. The particular objective of this past year has been to make progress on understanding entrainment at the top of cloudy boundary layers.

APPROACH

This research involves the utilization of the high resolution turbulent transport codes developed under previous ONR support to explore interesting cloud structure features which should be included in the subgrid parameterization of lower resolution models, as well as progress in modeling the conservation equations governing the cloud scale variance of temperature, humidity, and velocity, so that these variables may be included in larger scale models.

WORK COMPLETED

During the past year we have concentrated on understanding the results of our large-eddy-simulation (LES) investigation of the sensitivity of cloud-top entrainment to a number of variables, with particular emphasis on quasi-steady, buoyantly-driven boundary layers.

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**

4. TITLE AND SUBTITLE **Modeling of Cloud Scale Turbulent Transport**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **West Virginia University,MAE Department ,PO Box 6106,Morgantown,WV,26506**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Another important part of our effort over the current year has been continued participation in inter-model comparisons with the GEWEX Cloud Systems Studies boundary layer cloud modeling working group. Our LES results for a boundary layer with shallow cumulus from BOMEX were included in the 1997 Seattle workshop (Siebesma, 1997).

RESULTS

Lewellen and Lewellen (1997a,b) use large eddy simulations to strongly support the rather unexpected result that cloud top entrainment is often controlled by large eddy transport rather than the small eddies confined to the local mixing zone. In simulations of quasi-steady, buoyantly-driven boundary layers, the turbulent entrainment rate was found to be relatively insensitive to numerical or physical alterations which affect the small scale mixing dynamics near the inversion but leave the boundary layer scale eddy dynamics largely unchanged (e.g., changes in grid resolution, subgrid modeling, or modest wind shear). The entrainment rate is sensitive to changes which affect the large scale dissipation dynamics (e.g., low Reynolds number) as one might expect given that entrainment and dissipation are the two competing energy sinks in these systems.

We found a large eddy entrainment efficiency, η_E, which we defined as the fraction of the buoyant energy production going into entrainment rather than lost to turbulent dissipation, to be fairly constant over a wide range of quasi-steady, buoyantly driven boundary layers with broadly similar large eddy dynamics. As we have implemented it, η_E is similar (but not identical) to the flux partitioning measure of Stage and Businger (1981). Since this measure of entrainment cost is a global one, its implementation requires knowledge of boundary layer properties such as cloud fraction and depth; on the other hand it allows us to avoid defining a local buoyancy jump at z_i, which requires making assumptions about mixing at cloud top. This efficiency increases from approximately 0.3 for a surface driven dry boundary layer with a stable top, to ~0.35 for a top driven dry boundary layer with a stable top, and up to 0.5 for a quasi-steady boundary layer with an unstable cloud top with the cloud fraction reduced below one.

Entrainment results as parameterized by our entrainment efficiency, η_E, and the more traditional A parameter (The ratio of the entrainment velocity over the characteristic convective velocity, $w*$, times the Richardson number based on the virtual potential temperature jump ($\Delta\theta_V$) across the inversion, the mixed layer thickness (z_i), and $w*^2$ in the layer (i.e., Bretherton et al. 1997)) are summarized for many simulations in Fig. 1. Where possible, results from two different one hour averaging periods are included to give some idea of the time variability within a single simulation. The entrainment efficiency is seen to be fairly constant while the A parameter varies by more than an order of magnitude. There is in general a negative contribution to the buoyancy flux throughout the boundary layer arising from entrainment, as the warm air from above the inversion is mixed throughout the boundary layer down to the ground. Despite differences in inversion jumps and flux profiles, the boundary layer dynamics for the cases considered are broadly similar, being dominated

by large eddies spanning the boundary layer. The relative constancy of η_E follows as long as
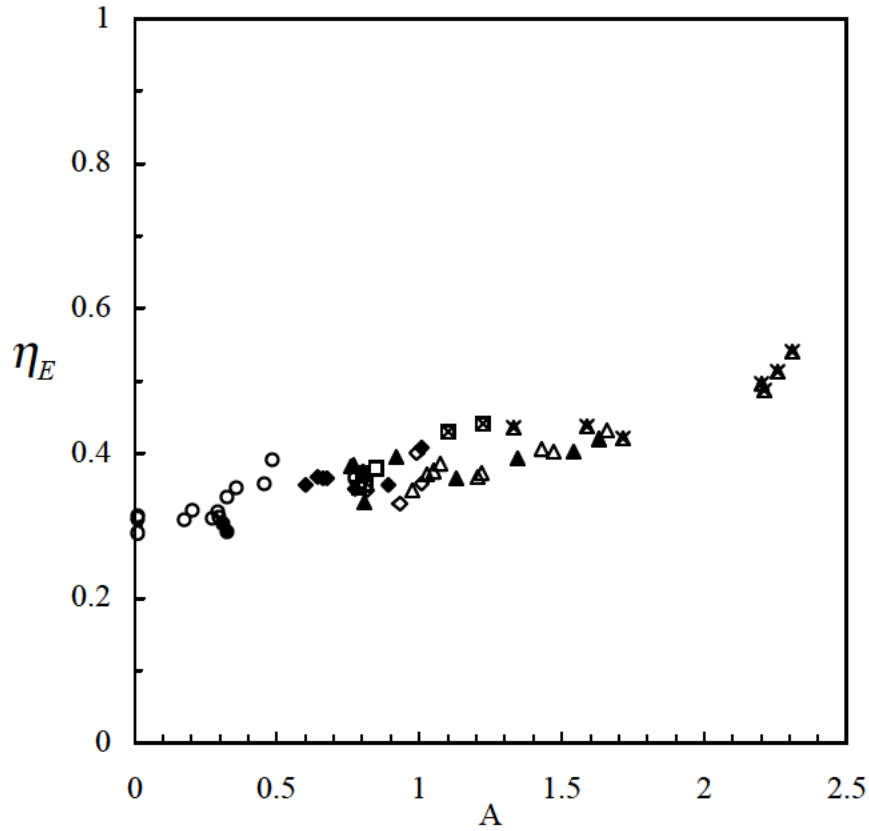

Fig. 1.   Summary of simulation results showing entrainment efficiency η_E versus the more traditional A parameter as defined in the text.   The simulation cases are labelled as follows: smoke cloud with surface heating (●); smoke cloud with cloud-top radiational cooling with different optical depths (◆); radiatively cooled smoke cloud with cooling height varied (o); radiatively cooled smoke cloud with varying wind shear (□); radiatively cooled water cloud with varying humidity jump across the inversion (Δ); radiatively cooled water cloud with L/c_p varied (▲); radiatively cooled water cloud with varying surface heat flux (◊). Those points overscored with "×" indicate unstable cloud tops.

the large scale mixing involved in the entrainment process is the dominant limiting factor setting the entrainment rate.

IMPACT

A consistent quantitative model of cloud top entrainment is important to any model which involves cloud dynamics. In addition to the navy's operational forecasting interest in clouds, an understanding of cloud dynamics on this scale is also a central issue in modeling global climate change.

TRANSITIONS

We sent information to Steve Burk, Marine Meteorology, Naval Research Laboratory, responding to his request for possible parameterization of the inversion thickness which might be used in radar refractivity estimates.

RELATED PROJECTS

The LES code developed under ONR support has been modified and used to model aircraft contrails for NASA (Lewellen and Lewellen, 1996), and to model the turbulent interaction of a tornado with the surface for NSF (Lewellen et al. 1997).

REFERENCES

Bretherton, C., M. MacVean, P. Bechtold, A. Chlond, W. Cotton, J. Cuxart, H. Cuijpers, M. Khairoutdinov, B. Kosovic, D. Lewellen, C-H. Moeng, P. Siebesma, B. Stevens, D. Stevens, I. Sykes, M. Wyant, 1997: An intercomparison of radiatively-driven entrainment and turbulence in a smoke cloud, as simulated by different numerical models. Submitted to *Quart. J. Roy. Meteor. Soc.*

Lewellen, D.C., and W. S. Lewellen, 1997a: Large Eddy Boundary Layer Entrainment. Submitted to *J. of the Atmospheric Sciences*.

Lewellen, D.C., and W.S. Lewellen, 1997b: LES Sensitivity Study of Cloud-top Entrainment. Proc. of the AMS 12th Symposium on Boundary Layers and Turbulence, Vancouver, BC, pp 100-101.

Lewellen, W. S., D. C. Lewellen, and Sykes, R.I., 1997: Large-eddy simulation of a tornado's interaction with the surface. *J. of the Atmospheric Sciences*, Vol. 54, 581-605.

Lewellen, D. C. and W. S. Lewellen, 1996: Large-Eddy Simulations of the Vortex-Pair Breakup in Aircraft Wakes. *AIAA J.*, Vol. 34, 2337-2345.

Siebesma, B., 1997: Model comparisons of the BOMEX shallow cumulus case for the 4th GCSS Boundary Layer Cloud Workshop, 24-25 July 1997, Seattle, Washington. Web site (http://www.knmi.nl/~siebesma/bomex.html).

Stage, S., and J. Businger, 1981: A model for entrainment into a cloud-topped marine boundary layer. Part 1: Model description and application to a cold-air outbreak episode; Part

II: Discussion of model behavior and comparison with other models. *J. of the Atmospheric Sciences*, **38**, 2213-2242.